SPATIAL CORRELATION OF AMPLITUDE ANOMALIES

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By

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SEISMIC DATA LABORATORY REPORT NO. 195

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AVAILABILITY

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ABSTRACT

Spatial correlations of amplitude anomalies have been conducted over LASA and LASA subarrays to test the hypothesis that these anomalies exhibit spatial stationarity. The evidence indicates that the anomaly process cannot be considered to be covariance stationary.

I. INTRODUCTION

This report describes results of part of a study of amplitude anomalies at LASA. The object of this part of the study was to see if these anomalies could be treated, in some sense, as a stochastic process.

It has been demonstrated[1,2] that the normalized short period peak-to-peak amplitudes of teleseismic events have a log normal distribution. That is, if the amplitudes of a set of events from the same geographic region are measured and their logarithms are taken, then we find that

$$\log a_{ij} = \log L_{ij} - \frac{1}{N} \sum_{j=1}^{N} \log L_{ij},$$

has a normal distribution. In this equation, the L_{ij} are either the measured peak-to-peak amplitudes at all elements in a LASA subarray or are the peak-to-peak amplitudes observed at the center elements of the subarrays. The index j is on the seismometer and i is an event index.

The distribution of log amplitudes is not normal if the collection includes all elements in LASA. The variance of log a_{ij} is larger in the case where the L_{ij} are the observed amplitudes at the center elements. The variances are the same at each subarray when the L_{ij} are the amplitudes of the elements in a subarray. Thus, these variances can be pooled after normalization.

These anomalies are assumed to be real in that a precisely repeated event should produce the same amplitudes at the seismometers as the original. The anomalies vary however for events from the same geographic region and it is unlikely that a calibration of the earth would be a practical procedure with which to eliminate anomaly effects. Rather, a statistical approach may be a more reasonable way to proceed.

The fact that the anomalies in the subarrays can be pooled after normalization suggests that one may successfully hypothesize that these anomalies exhibit spatial stationarity. That is, although there may be slowly varying anomaly effects with distance*, with these removed the expectation of a particular amplitude anomaly is independent of spatial location.

Beyond this we desire that the anomaly process be covariance stationary. If this is so then the covariance function will serve as a measure of the distance which should be placed between seismometers so that they will exhibit independent amplitude estimates. Further, since the anomalies are log-normal no other statistic is needed since the covariance function is a complete statistic for normally distributed variables.

2. SPATIAL CORRELATIONS OVER LASA

This section investigates the possibility of correlation among the peak-to-peak amplitudes across all of LASA. Data used were from eleven Fiji Island earthquakes which occurred at 243° azimuth and from 9,500 km to 10,500 km distance from the center of LASA.[3] From these eleven events, correlation coefficients were computed as spatial displacements were made over LASA. In the computations, the logarithms of the normalized data are used for the reasons cited in the introduction of this report. We define the estimate of the coefficient of correlation to be

$$r = (\Sigma X_i Y_i) / (\Sigma X_i^2)^{1/2} (\Sigma Y_i^2)^{1/2}, \tag{1}$$

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* We note, however, that on a larger scale, these slow variations also are distributed as log normal.

i. e. we have set the mean of X and of Y to be zero. The justification for pre-determining X and Y is as follows: the estimate of the coefficient of correlation is generally defined to be

$$r = \frac{\hat{\mathrm{Cov}}\ (X, Y)}{\sqrt{\hat{\mathrm{Var}}\ X}\ \sqrt{\hat{\mathrm{Var}}\ Y}}$$

which for small samples turns out to be

$$r = \frac{(N-1)\ \Sigma\ (X_i-\bar{X})\ (Y_i-\bar{Y})}{\sqrt{(N-1)\ \Sigma\ (X_i-\bar{X})^2}\ \sqrt{(N-1)\ \Sigma\ (Y_i-\bar{Y})^2}} = \frac{\Sigma(X_i-\bar{X})\ \ (Y_i-\bar{Y})}{\sqrt{\Sigma(X_i-\bar{X})^2}\ \ \sqrt{\Sigma(Y_i-\bar{Y})^2}} \qquad (2)$$

Now r is the coefficient of correlation for the two dimensional distribution of (X, Y). But the instruments that make up X and Y are actually subsets of the set, say, Z which contains the 21 subarray center seismometers. Since X and Y are samples of Z, and since we seek the mean of the population from which X and Y were drawn, it is reasonable to use Z as a better estimate of the population mean than that given by either $\bar{X}$ or $\bar{Y}$. Due to the normalizing process, $\bar{Z}$ is zero. Setting $\bar{X} = \bar{Y} = \bar{Z} = 0$ in (2) yields the equation given by (1). In addition, another degree of freedom is gained in estimating the coefficient of correlation since the mean is not estimated. We will apply equation (1) throughout the remainder of this report for all calculations of the coefficient of correlation.

A. <u>LASA Spatial Correlations Using Average Log of Normalized Peak-To-Peak Amplitudes</u>.

Since all eleven events were relatively closely grouped in comparison to the overall path, the average of the logarithms of the normalized peak-to-peak amplitudes at a given subarray was used as an estimate of the true value for that subarray (cf. Table I).

These average values were used in the calculations of the spatial correlation coefficients. Correlations were computed along a line parallel to the incoming signal (243° az.) and another set along a line perpendicular to the incoming signal (153° az.). Due to the configuration of LASA, few displacements exist where enough subarrays intersect to compute a valid coefficient of correlation. Table II lists the subarrays which were selected as intersecting at various displacements. Figure 1 presents the coefficients of correlation plotted against the spatial shifts using the average logarithm of the normalized peak-to-peak amplitudes over all events as the estimate of the true value for each subarray. The numerical values are shown in Table III, Part A.

B. LASA Spatial Correlations of Single Events

The correlation coefficients for the individual events were computed. That is, each event was considered singly as the spatial shifts were made across LASA at 153° and 243° azimuth as in A. The coefficients are presented in Table III, Part B. Figures 2 through 11 show the behavior of the coefficients as the spatial displacements are made. Note that Table III, Part C, contains the average coefficient of correlation, $\bar{r}$, for various displacements, and Figure 12 presents the graph of $\bar{r}$ vs. the spatial shifts. It is of interest to compare the graphs of Figures 1 and 12, i.e. the coefficient of correlation of the average normalized amplitudes vs. displacement against the average coefficient of correlation of the individual events vs. displacement.

3. SPATIAL CORRELATIONS OVER LASA SUBARRAYS

After examining correlations over all LASA, we directed our attention to spatial correlations over subarrays. The concept of spatial shifting over a subarray is the same as that over all of LASA except that unlike LASA the configuration of a subarray is well defined in terms of concentric circles and radial spokes every 60^{o}. The spatial shifts over the subarrays were made along the legs (radial spokes) in this instance rather than with respect to the origin of the event.

A. <u>Subarray Spatial Correlations for Single Events</u>

Three N. Colombia events (21 Dec. 65; 21 April 66; 12 June 66) were chosen on the basis of availability of complete tapes of all 525 instruments in LASA for events which originated very close together. Again the logarithms of the normalized data were used to compute the coefficient of correlation and the means of the data samples were set to zero as motivated in Section 2, LASA. As spatial displacements were made across each subarray (at 0.5 km increments), coefficients of correlation were computed and graphs of coefficients vs. displacement were drawn for each leg for every subarray. Some representative graphs are given in Figures 13 through 18. The patterns in the graphs were cross-checked among the same subarrays for all three events and among similarly oriented subarrays for the same event. No consistent relationships were discovered with this approach. Contouring (Figures 19 and 20 are two examples) seemed to suggest certain patterns (viz., that the contour "pointed" towards the direction of the event) and some consistencies were found, but the presence of exceptional and contradictory contours made such a conclusion at best doubtful. It was thought that teleseismic explosions occurring close together might be better sources to study for contouring in this manner. This step is taken in 3-C below, but first we will mention some additional investigation of the three N. Colombia events.

B. Testing For Correlation Among Three Colombia Earthquakes

Coefficients of correlation were computed over each subarray for paired events using the normalization described earlier and equation (1). That is, the twenty-five readings of the A subarray for, say, the 21 December 1965 earthquake, were tested against the respective twenty-five readings of this subarray for, say the 21 April 1966 earthquake. The three independent earthquakes yield three distinct pairs for testing in this manner, and each pair of events has a maximum of twenty-one coefficients to be computed... one coefficient corresponding to each subarray.

In nearly every case, the coefficient was significant (i.e. correlation existed) and in many cases (nearly two-thirds) the coefficients were between .8 and 1.0. Table IV summarizes the results of these calculations. This test can be considered as examining the correlation among the instrument responses as the source distance is varied. In the next step, the converse of this procedure was done ... the respective elements for similarly oriented subarrays (account being taken for long and short configurations) were inspected for correlation for each earthquake. This time, correlations were not detected with the exception of one case which may be ascribed to chance (cf. Table V).

C. Subarray Spatial Correlations For Two Shots

Two nuclear shots from Kazakh (November 21, 1965; February 13, 1966) were selected to compare with the results of the three Colombian earthquakes. The correlation coefficients were contoured as had been done of the earthquakes, and a search was made to detect similar patterns between the same subarrays for the two shots. The number of similarities found was no greater than that expected purely by chance.

D. Testing For Correlation Between Two Kazakh Shots

The coefficient was computed over each subarray for both events as was described in 3-B. Six of the subarrays registered a positive correlation, one a negative, and the remaining thirteen (one subarray was inoperative) no correlation, as is shown in Table VI. Performing the converse test on this data provided results similar to those obtained from the earthquakes, i.e., no correlations were detected among similarly oriented subarrays for the same event (cf Table VII).

4. CONCLUSIONS

Only tentative conclusions can be drawn from this data. The sparce sampling of the LASA array limits the reliability of the correlation coefficients which were computed. For this reason a uniformly spaced grid of seismometers would have aided this study.

It is likely that the anomaly process cannot be considered to be spatial covariance stationary. Since this process, is in fact, a description of the underlying geology one might have hypothesized this from the beginning. The author does not have a simple explanation for the log-normal distribution of the anomalies or for their apparent stationarity although this too reflects the geology.

REFERENCES

1. Broome, P. W., Frankowski, D. E., and Klappenberger, F. A., 9 January, 1967, "Amplitude Anomalies at LASA", Report No. LL-4, Applied Research, Teledyne, Inc., Alexandria, Virginia.

2. Klappenberger, F. A., 9 June, 1967, "Distribution of Short Period P-Phase Amplitudes over LASA", Report No. 187, Teledyne, Inc., Alexandria, Virginia.

3. The dates of the events are: February 4, February 8, February 17, February 26, March 10, March 12, March 20, April 16, April 25: all in 1966.

TABLE I

Logs of Normalized P-P Amplitudes

Subarray Designation \ Event Number	152	171	197	219	238	247	253	254	271	342	359	AVG.LOG.
B1	-.086	.143	-.022	-.108	.140	.057	.061	-.168	.033	-	.086	.014
B2	.065	.013	.061	-.260	-.018	-.009	-.056	.013	-.125	-	-.125	-.044
B3	.061	.061	-.097	.137	.068	.137	.045	.041	-.041	-	.017	.043
B4	.100	.230	.310	-.027	.025	.104	.299	.041	.117	-	.204	.140
C1	-.013	-.013	-.097	-.036	.283	.146	.086	.134	.274	-.092	-	.067
C2	-.292	-.102	-	-	-.495	-.310	-.208	-.208	-.276	-	-.125	-.224
C3	-.066	.161	-.097	.107	.107	.057	-.155	.065	-.041	-	.228	.037
C4	.009	-.137	-.398	-.027	.258	.093	.104	.076	.068	-	-.027	.002
D1	.193	-.013	.310	.369	.408	.270	-.027	.204	-	.100	-	.202
D2	-.244	-	-.301	-	-.125	.045	-.081	-	-	-	-	-.141
D3	.041	-.041	.253	.009	-.276	-	-	-	-	.283	.086	.051
D4	-.229	-.377	-	-.284	-.018	-.187	-.086	-.013	-.032	-.168	-.071	-.147
E1	-	-.137	-	-.041	-.125	-.187	-.284	-	-.125	-.032	-.252	-.148
E2	-	-.071	-	-	-.495	-.252	-	-.585	-.161	-.066	-.125	-.251
E3	.009	-.444	-	-.108	-.367	-	-.051	-.018	-	-.420	-	-.200
E4	.076	.427	-.046	.124	.350	-.009	.155	.170	.230	.004	-	.148
F1	-	-	-	-	.107	-.108	-	-	-.149	-	-.181	-.083
F2	.223	.230	-.071	-.102	.107	-.009	-.004	-.027	-.086	.188	.086	-.049
F3	.352	.179	.277	.161	.204	.223	.250	.188	.086	-	.297	.222
F4	-.143	-.215	-.022	-.009	-	-.125	-.161	-.081	.152	.025	-.125	-.070
AO	-.066	.104	-.046	.093	-.125	.057	.107	.167	.076	.179	.017	.051

TABLE II

Intersecting Subarrays For Various Displacement Distances and Azimuths Used In Spatial Correlation

A. Direction of Displacement - 247°

± 10 km	± 18 km	± 22 km
C1, B4	B3, D3	AO, D3
B1, AO	B1, B3	C1, C4
C2, B2	D1, B1	B1, B3
B2, C3	C1, C4	C2, C3
AO, B3	C2, C3	D1, B1
B4, C4		

B. Direction of Displacement - 153°

± 10 km	± 17 km	± 25 km
B3, C4	D2, B2	D2, B4
C3, B3	B2, B1	B2, D4
C2, B1	C3, C4	D1, E1
AO, B4	B4, D4	
B1, C1	C2, C1	

± 80 km	± 90 km
E3, E4	F4, AO
F2, D2	E1, F2
B4, F4	C3, E2

This table lists the intersecting subarrays for various displacement distances and azimuths which were used in the spatial correlation described in the report text.

TABLE III

Coefficients of Correlation For Individual Events At Designated Spatial Shifts

	Direction of Displacement-243°			Direction of Displacement-153°					
	Displacement, km			Part A					
	±10	±18	±22	±10	±17	±35	±80	±90	
Coeff. of Correl. of Avg. Logs	.447	-.087	-.105	.173	-.584	-.687	-.604	-.128	cf.Fig 1
PART B									
Event Nos.									
152	-.403	-.004	-.112	.341	-.401	X	-.950	X	
171	-.121	-.207	-.221	.108	-.829	X	X	-.826	
197	-.877	.057	.141	.469	.146	X	X	X	
219	-.389	-.724	-.753	.374	.381	X	X	X	
238	-.029	.224	.395	-.035	-.530	-.979	X	X	cf.Figs 2-11
247	.491	.236	.236	.194	-.689	-.567	X	-.330	
253	.592	.894	.894	.227	-.797	-.273	-.773	X	
254	-.206	-.615	-.615	.328	-.506	X	X	X	
271	.880	.820	.820	.085	-.921	X	X	.727	
359	-.223	-.686	-.686	-.066	-.828	X	X	-.946	
PART C									
Avg. Coef. of Correl. of Each Event, $\bar{r}$	-.028	-.001	-.010	.203	-.498	-.606	-.861	-.344	cf.Fig. 12

TABLE IV

Subarray correlations for the Colombia Earthquakes

	21 Dec 65 / 21 Apr 66		21 Dec 65 / 12 Jun 66		21 Apr 66 / 12 Jun 66	
	Computed r	Critical r, 5%	Computed r	Critical r, 5%	Computed r	Critical r, 5%
B1	0.693	0.388	0.613	0.388	0.537	0.388
F3	0.955	0.388	0.851	0.388	0.776	0.388
F4	0.987	0.388	-0.477	0.388	-0.503	0.388
AO	0.418	0.388	0.637	0.388	0.235	0.388
B3	0.815	0.388	0.754	0.388	0.959	0.388
C4	0.733	0.396	0.933	0.388	0.943	0.396
B4	0.815	0.388	0.754	0.396	0.790	0.396
C1	0.939	0.388	0.893	0.388	0.844	0.388
C2	0.898	0.388	0.782	0.388	0.639	0.388
B2	0.857	0.388	0.767	0.388	0.945	0.388
C3	0.902	0.388	0.746	0.388	0.836	0.388
D3	0.986	0.388	0.977	0.388	0.979	0.388
D4	0.563	0.388	0.368	0.388	0.634	0.388
D1	0.831	0.404	0.882	0.404	0.931	0.388
D2	0.412	0.396	0.452	0.388	0.511	0.396
E3	0.945	0.388	0.815	0.388	0.843	0.388
E4	0.450	0.388	0.511	0.388	0.805	0.388
E1	0.900	0.388	0.825	0.388	0.806	0.388
F1	0.956	0.388	0.916	0.388	0.898	0.388
E2	0.873	0.388	0.889	0.388	0.901	0.388
F2	0.956	0.388	0.860	0.388	0.860	0.388

Subarray correlations for the Colombia earthquakes

The critical values are determined by using the "t" distribution where

$$t = r\left(\frac{n-1}{1-r^2}\right)^{\frac{1}{2}}$$

A detailed explanation is presented in Snedecor's "Statistical Methods" Fifth Edition, pp 173, 174.

TABLE V

Correlations of Similarly Oriented Subarrays
For The Colombia Earthquakes

	21 Dec. 1965		21 Apr. 1965		12 Jun. 1965	
	Computed r	Critical r, 5%	Computed r	Critical r, 5%	Computed r	Critical r, 5%
C4, E1	0.239	0.388	0.232	0.396	0.121	0.388
B1, C2	0.082	0.388	0.060	0.388	0.257	0.388
B1, D2	0.200	0.388	-0.068	0.396	0.239	0.388
B1, E3	0.332	0.388	0.195	0.388	0.495	0.388
C2, D2	-0.137	0.388	-0.137	0.396	-0.340	0.388
C2, E3	0.005	0.388	-0.033	0.388	0.143	0.388
D2, E3	0.227	0.388	0.042	0.396	0.108	0.388

TABLE VI

Subarray Correlations For The Two Kazakh Explosions

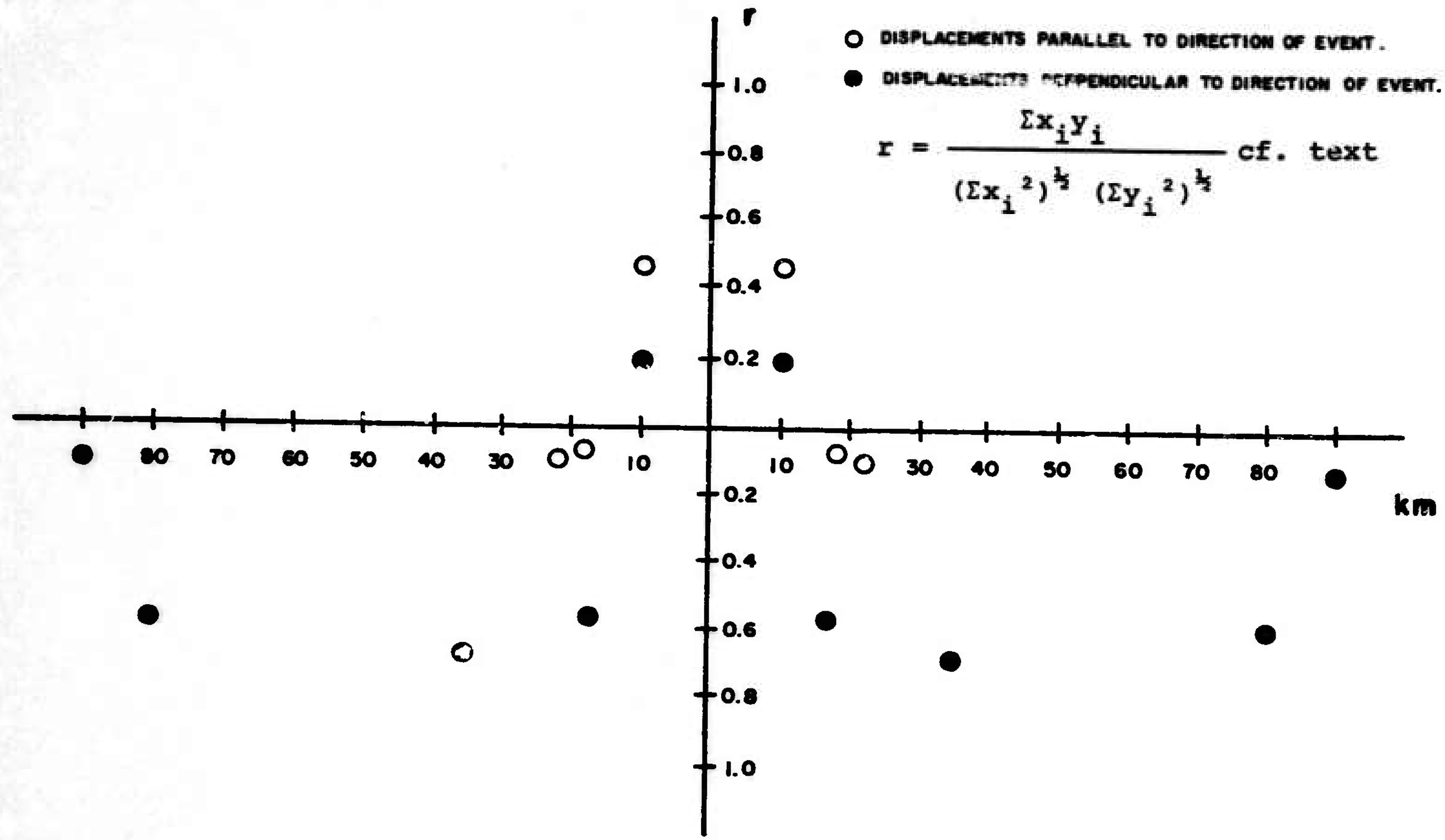
Subarray Designation	Coeff. of Correlation	Critical r, 5%
B1	0.067	0.388
F3	0.021	0.388
F4	-0.042	0.388
AO	0.615	0.388
B3	0.898	0.388
C4	0.905	0.388
C1	0.276	0.388
C2	-0.264	0.388
B2	-0.157	0.388
C3	-0.030	0.388
D3	0.275	0.388
D4	0.300	0.388
D1	0.333	0.388
D2	0.071	0.388
E3	0.554	0.388
E4	0.788	0.388
E1	0.044	0.388
F1	-0.573	0.398
E2	0.595	0.388
F2	0.220	0.388

Subarray correlations for the two Kazakh explosions.

TABLE VII

Correlations of Similarly Oriented Subarrays
For The Kazakh Explosions

	21 Nov. 1965		13 Feb. 1966	
	Computed r	Critical r, 5%	Computed r	Critical r, 5%
C4, E1	-0.075	0.388	-0.062	0.388
B1, C2	0.068	0.388	0.021	0.388
B1, D2	0.159	0.388	-0.282	0.388
B1, E3	0.170	0.388	0.024	0.388
C2, D2	0.229	0.388	0.294	0.388
C2, E3	0.214	0.388	-0.175	0.388
D2, E3	-0.240	0.388	-0.117	0.388



$$r = \frac{\Sigma x_i y_i}{(\Sigma x_i^{\,2})^{\frac{1}{2}} \, (\Sigma y_i^{\,2})^{\frac{1}{2}}} \quad \text{cf. text}$$

Figure 1.

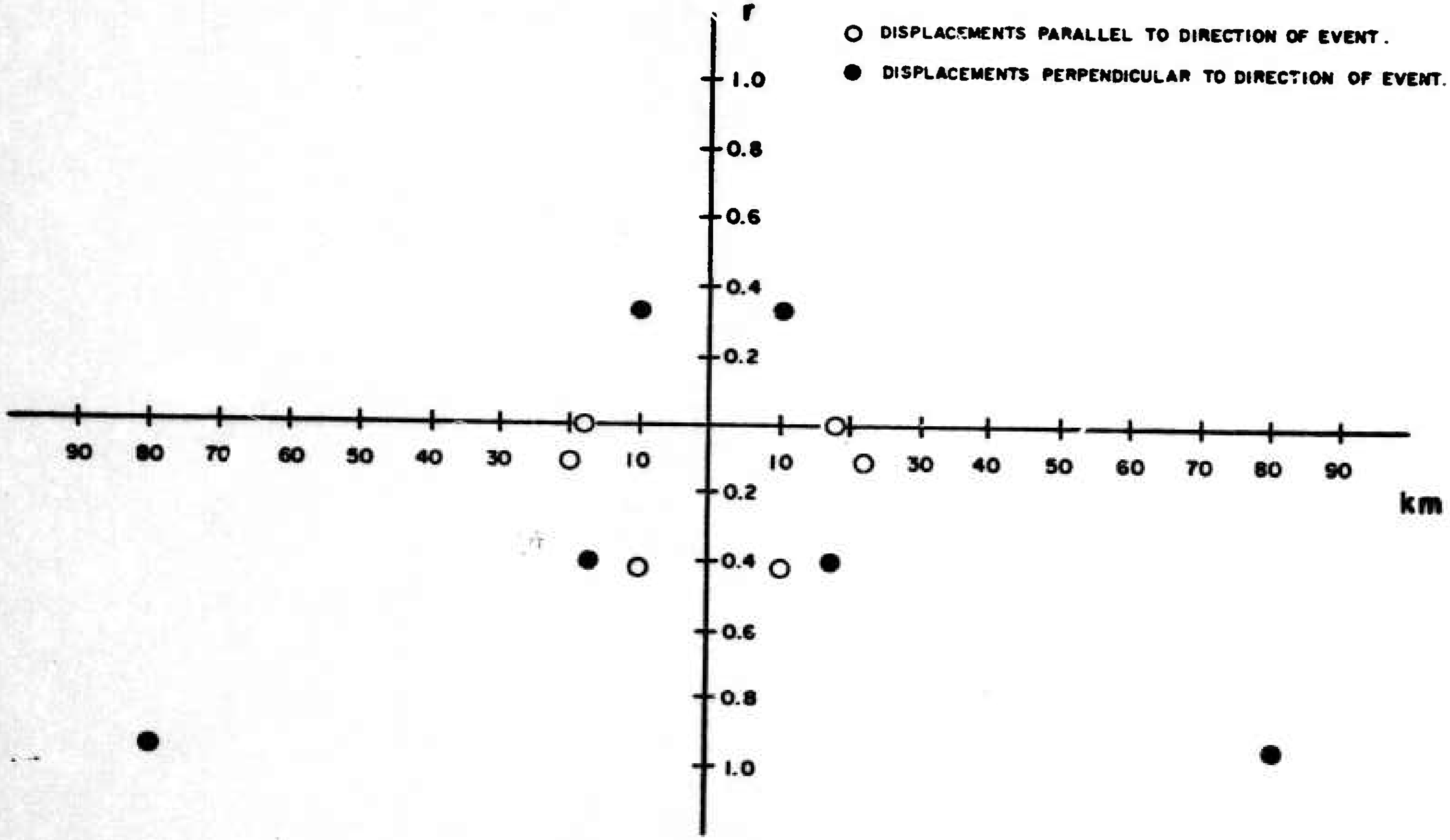


Figure 2. Event 152

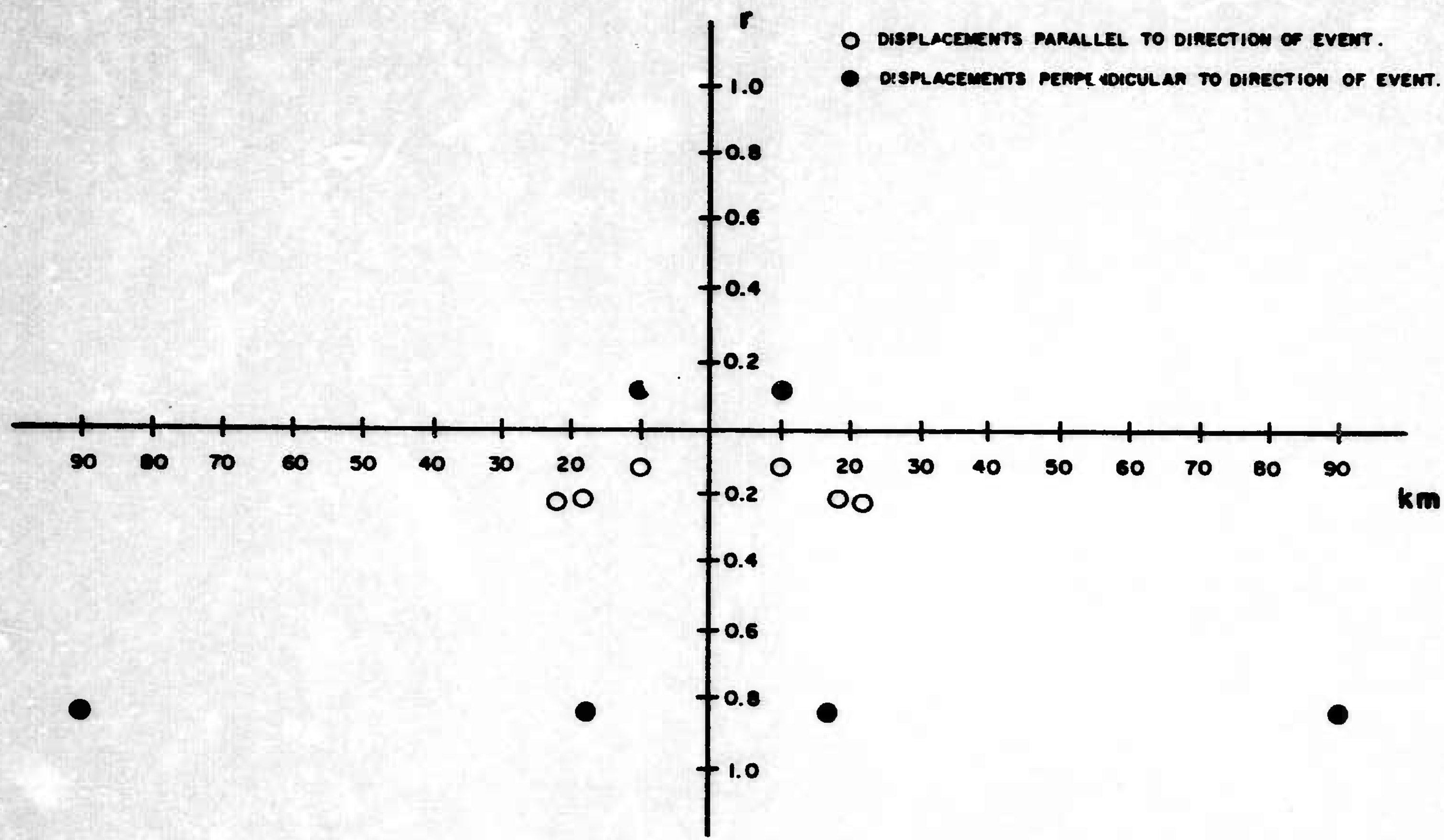


Figure 3. Event 171

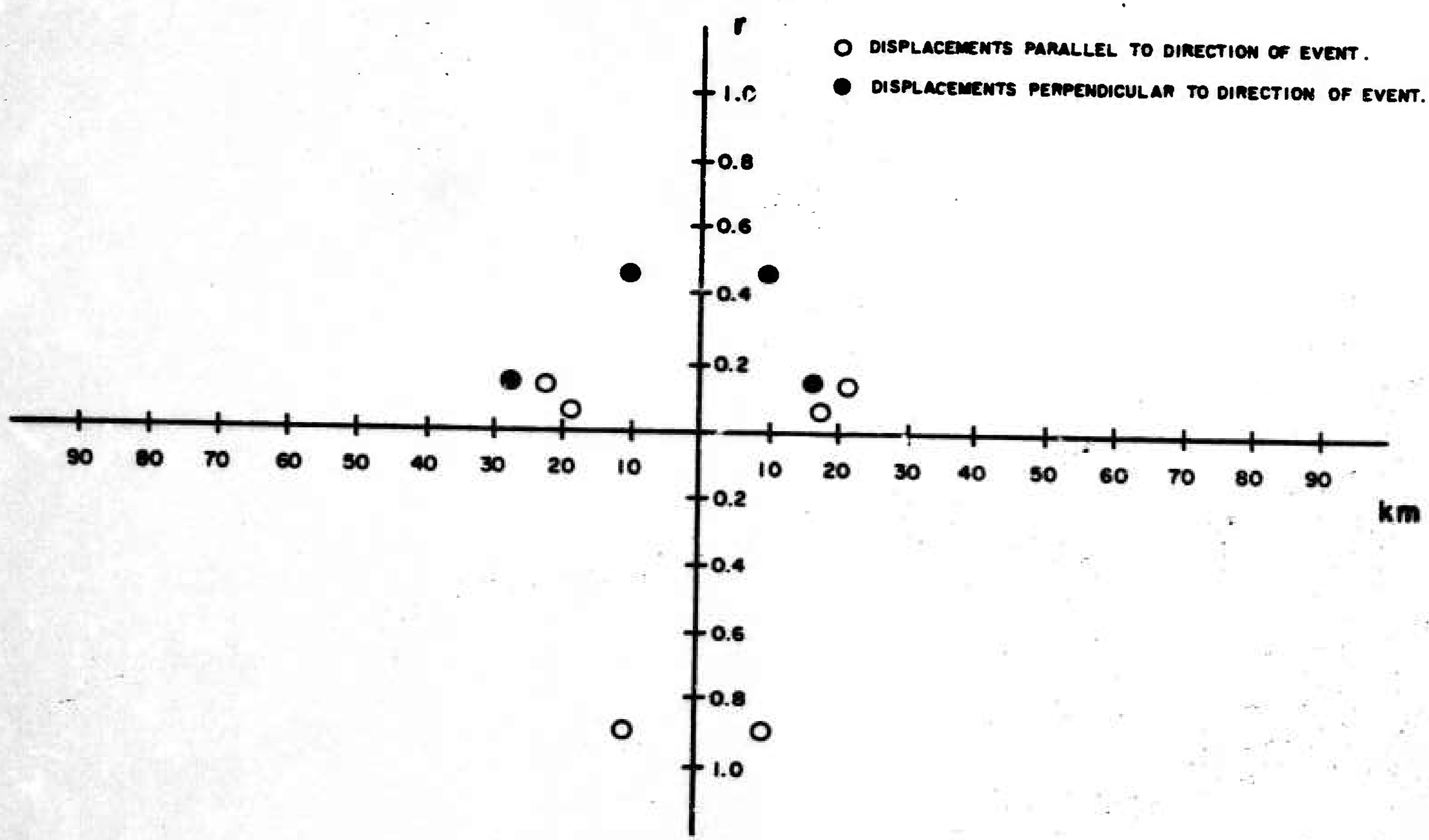


Figure 4. Event 197

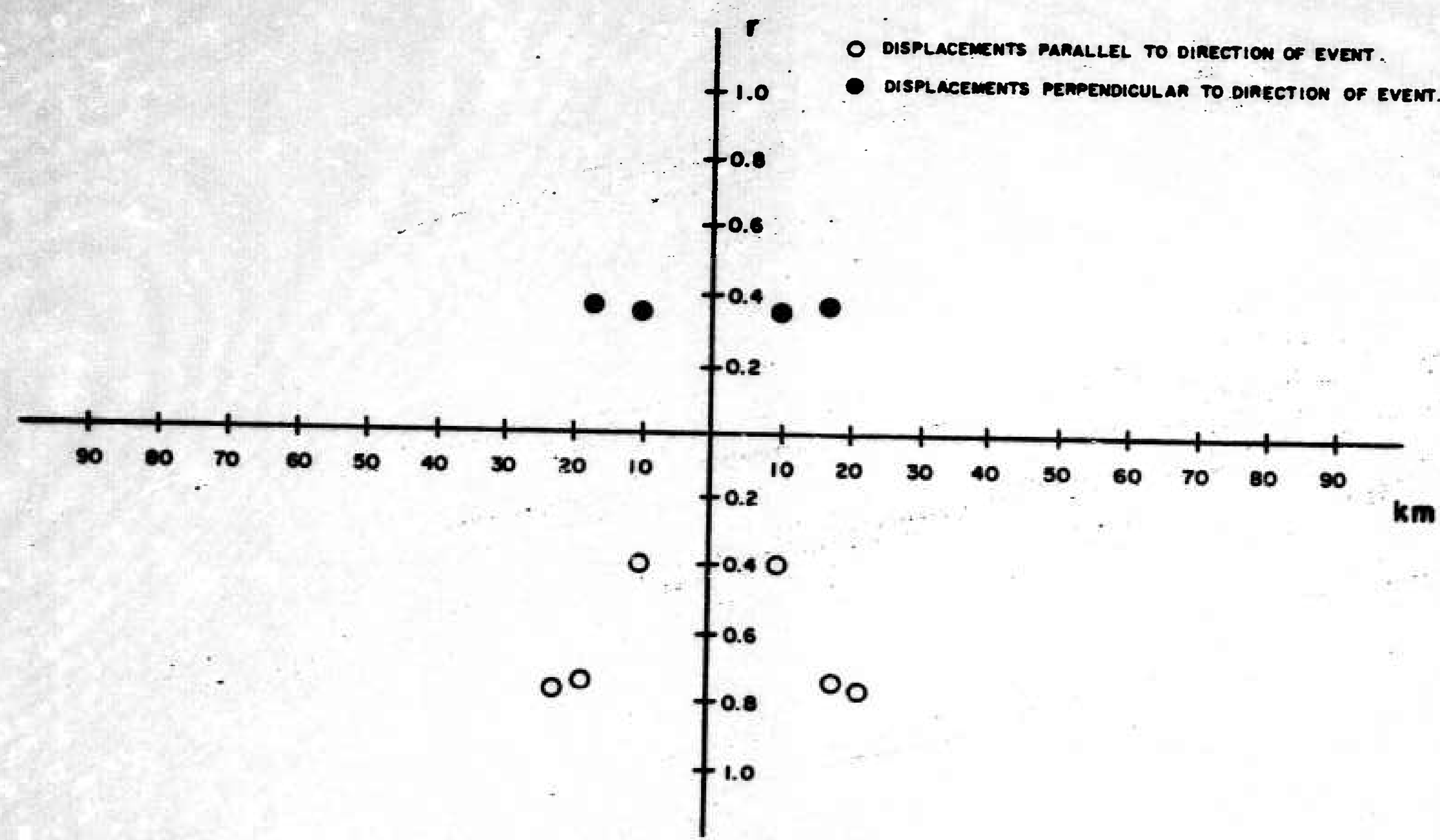
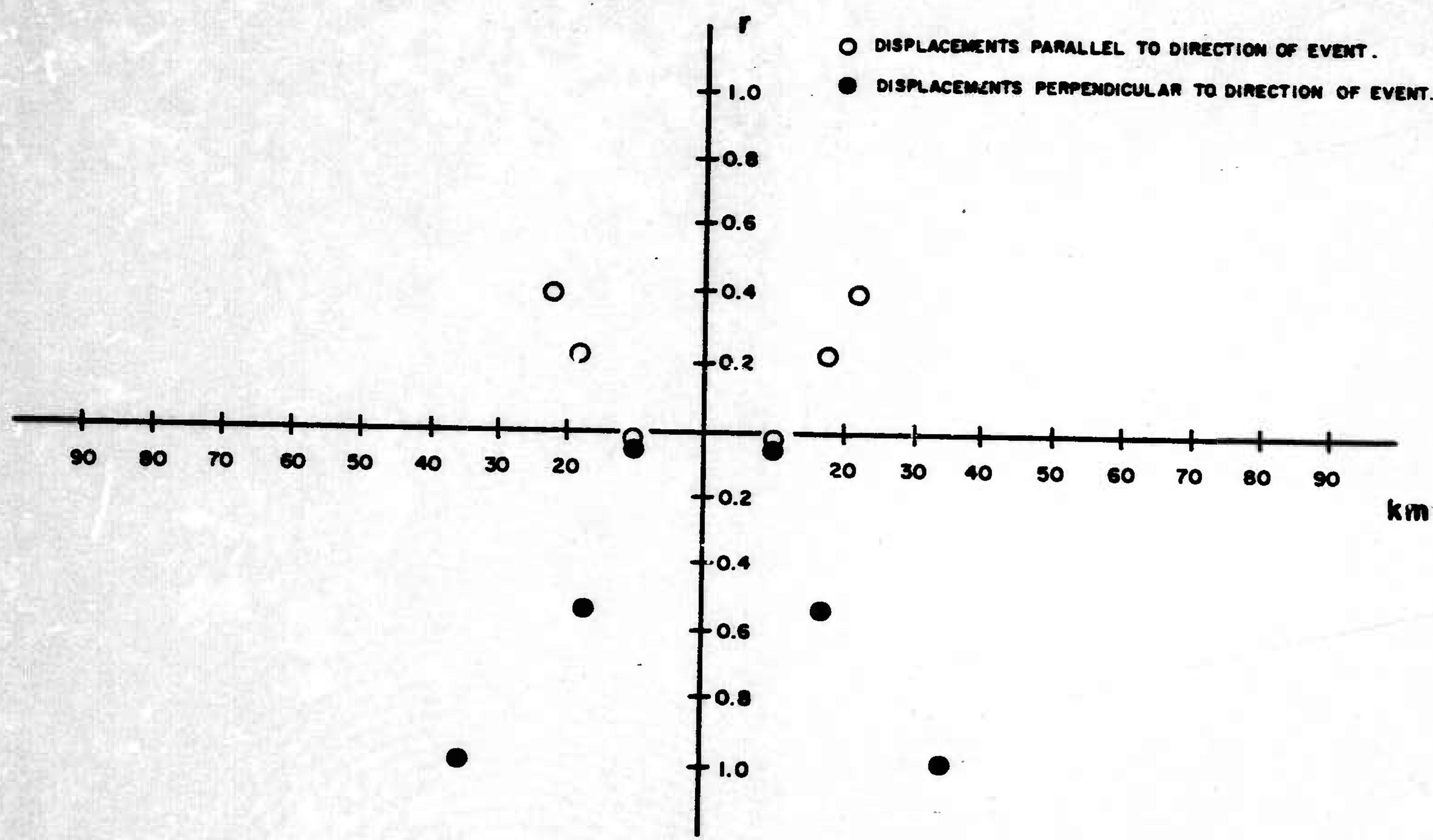


Figure 5. Event 219



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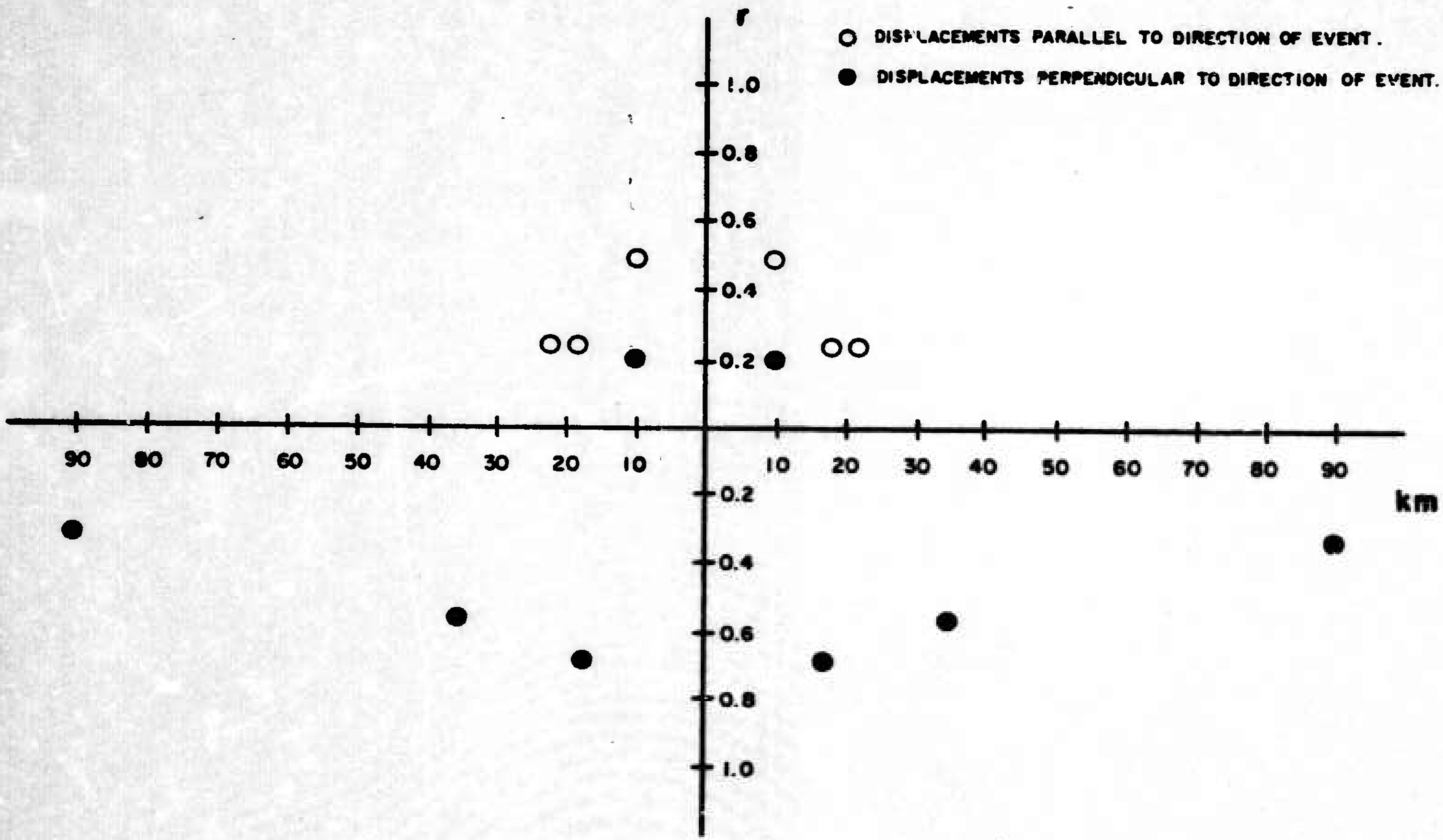
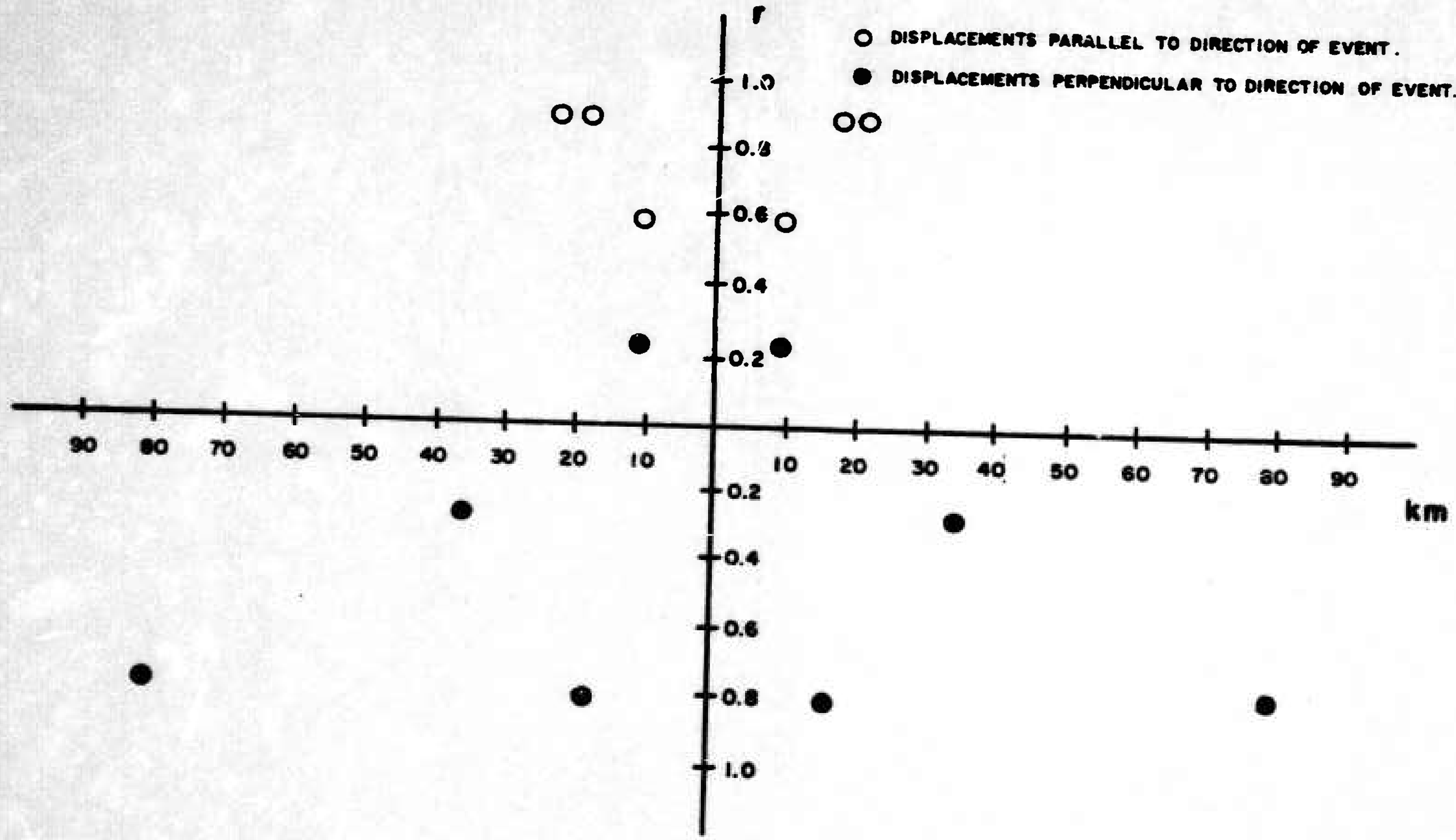


Figure 7. Event 247



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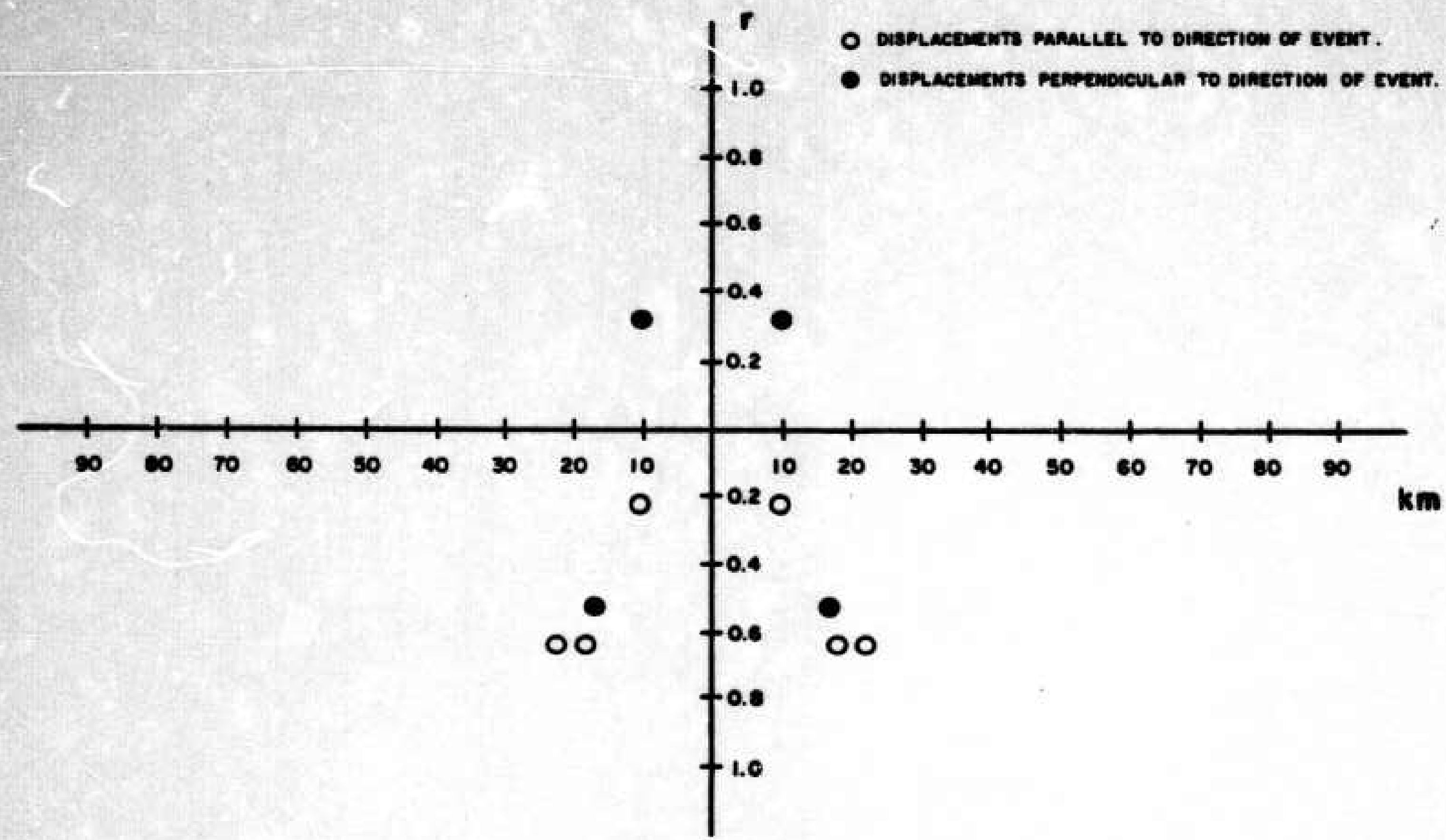

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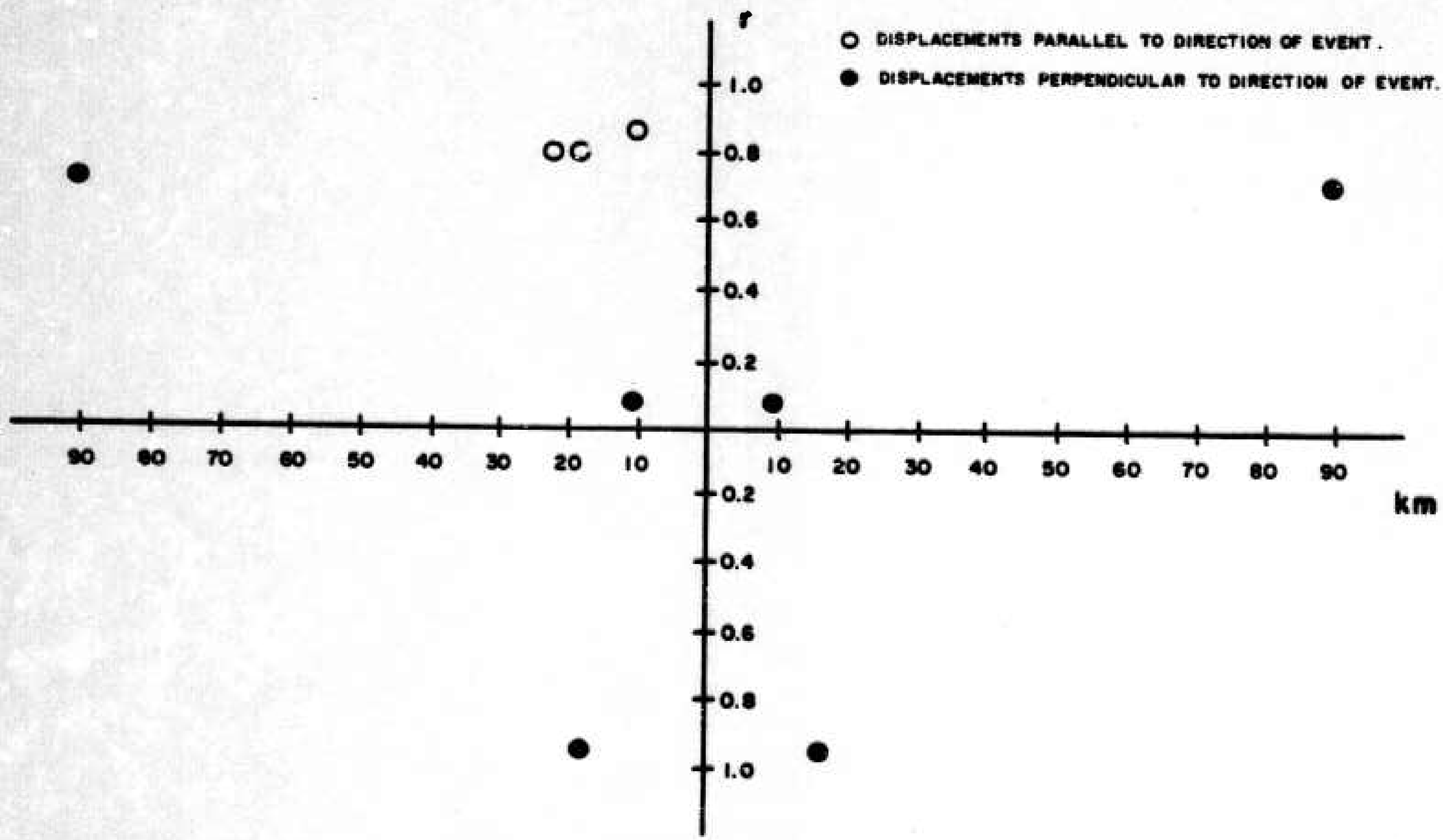
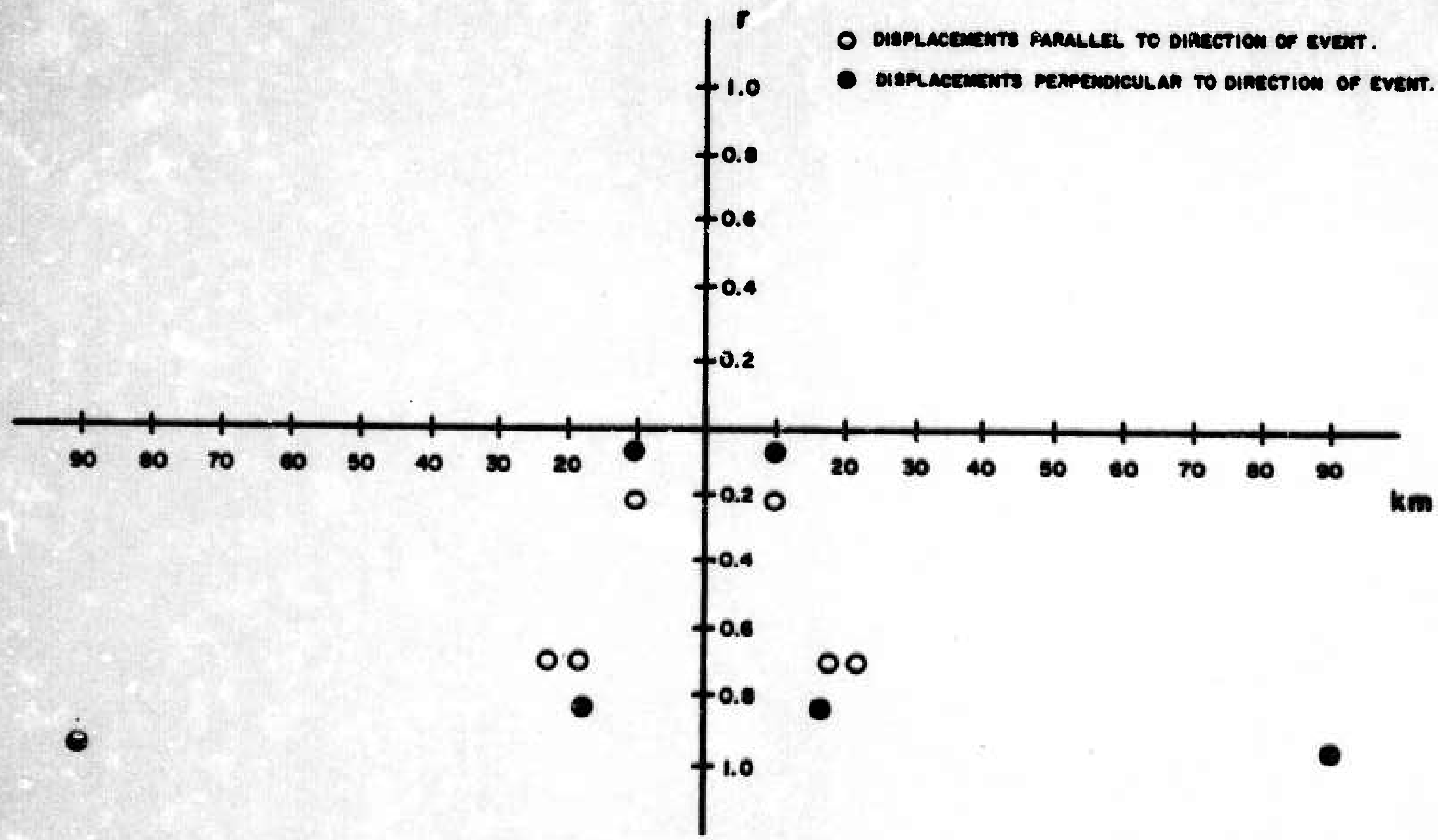


Figure 10. Event 291



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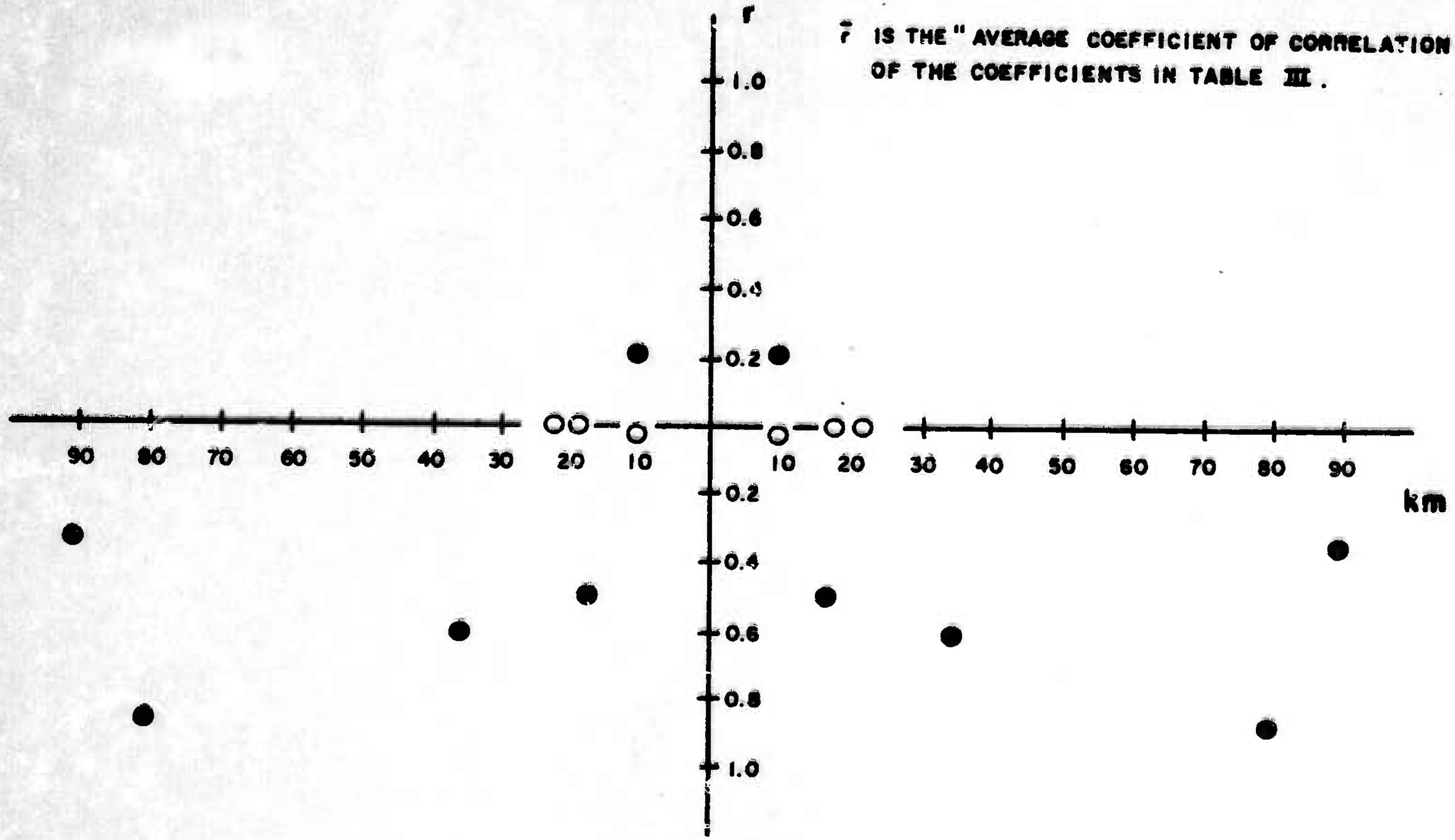

r
$\bar{r}$ IS THE " AVERAGE COEFFICIENT OF CORRELATION " OF THE COEFFICIENTS IN TABLE III.
1.0
0.8
0.6
0.4
0.2
90 80 70 60 50 40 30 20 10
10 20 30 40 50 60 70 80 90
km
0.2
0.4
0.6
0.8
1.0

Figure 12.

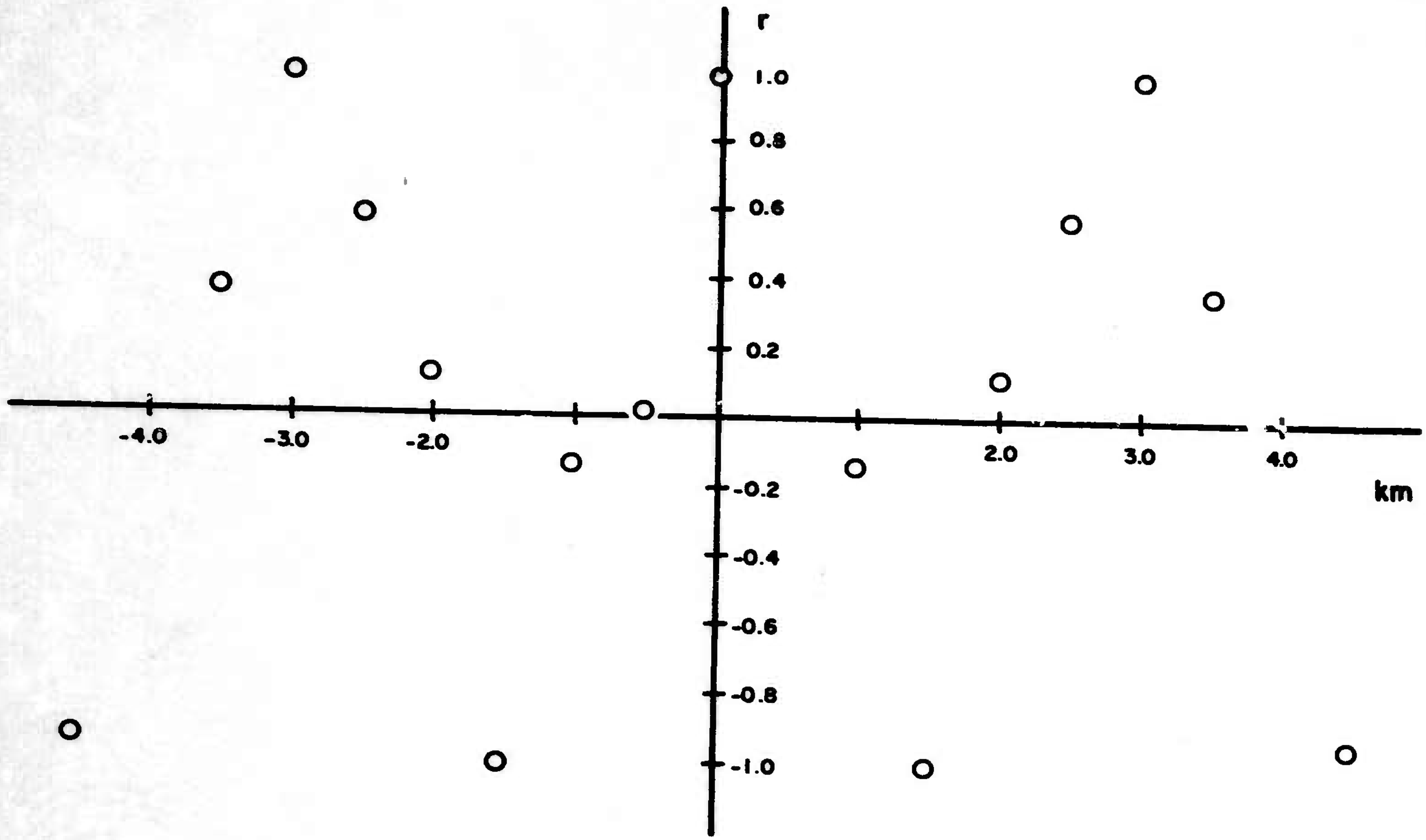

Figure 13. N. Colombia, 21 December 1965
Seismogram No. 6393,C4,Leg 1

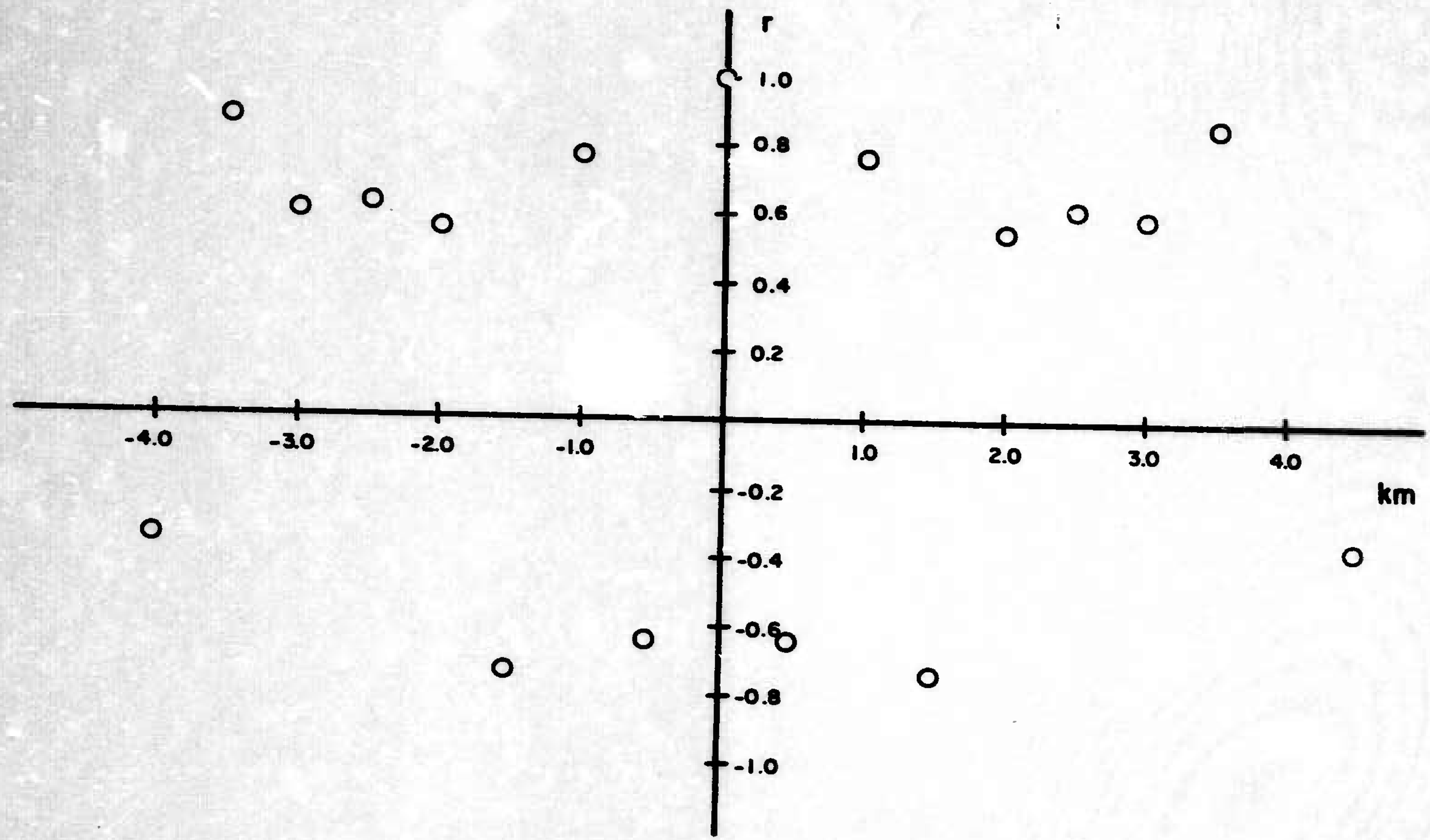

Figure 14. N. Colombia, 21 December 1965
Seismogram No. 6393,C4,Leg 2

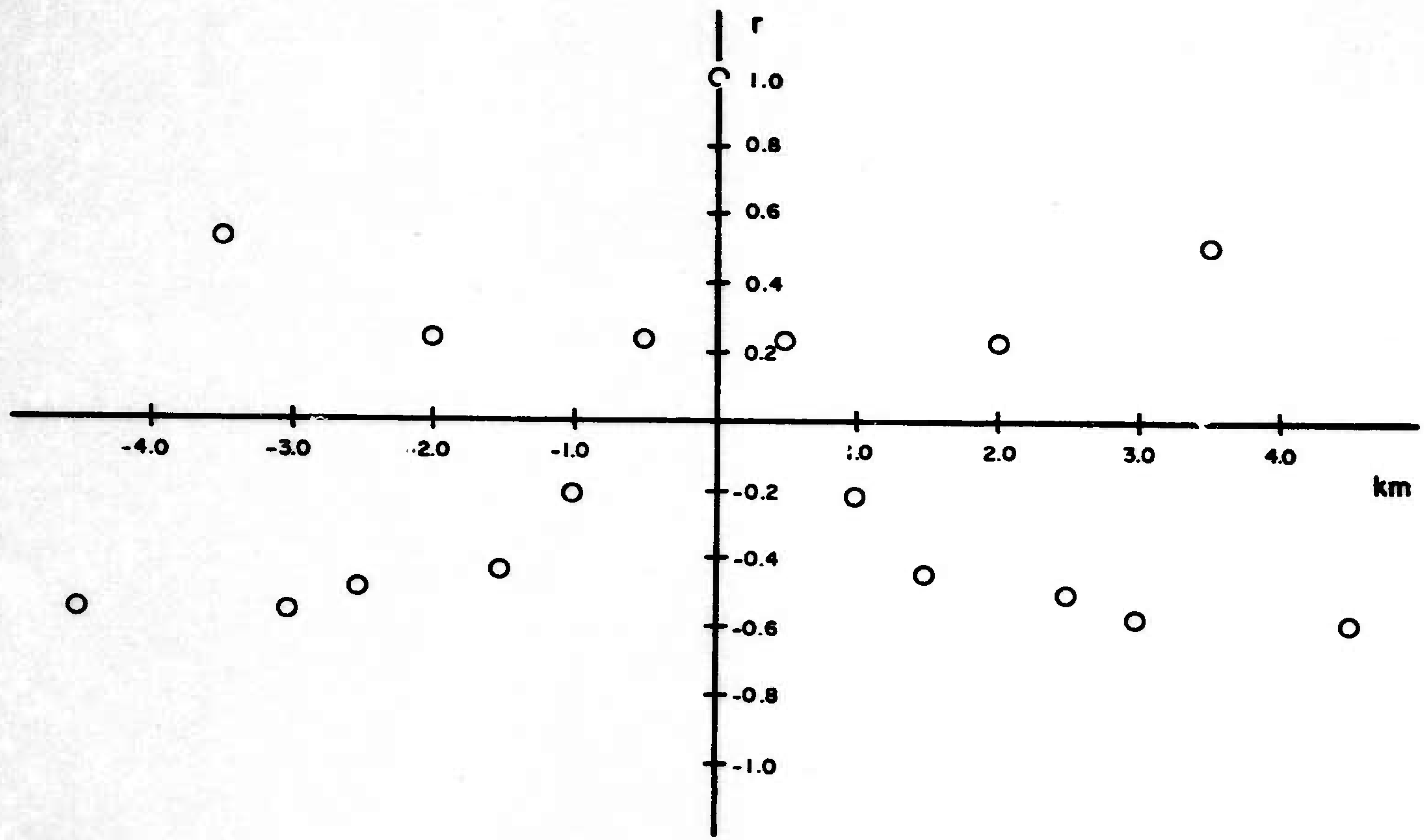

Figure 15. N. Colombia, 21 December 1965
Seismogram No. 6393,C4,Leg 3

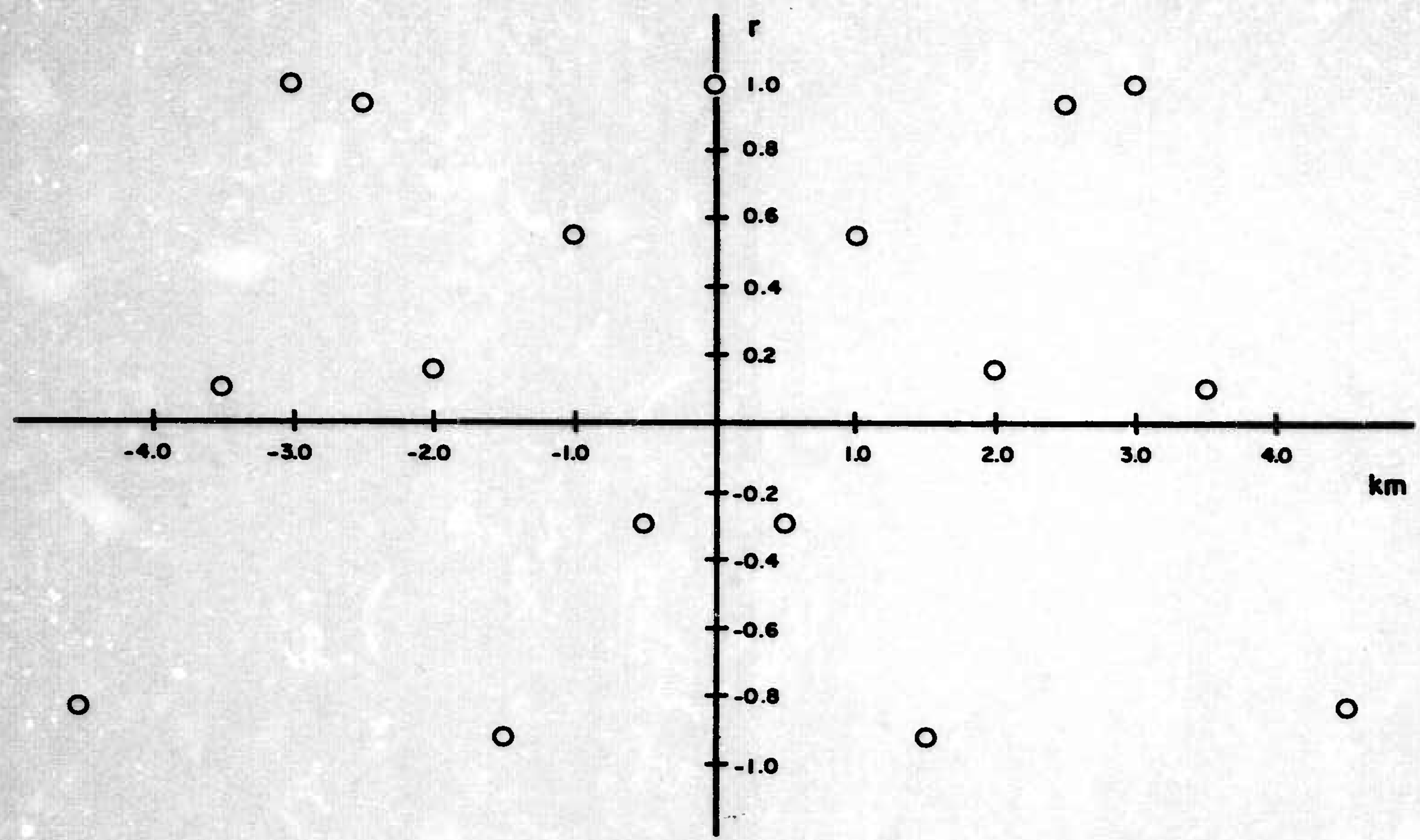

Figure 16. N. Colombia, 12 June 1966
Seismogram No. 7635, C4,
Leg 1

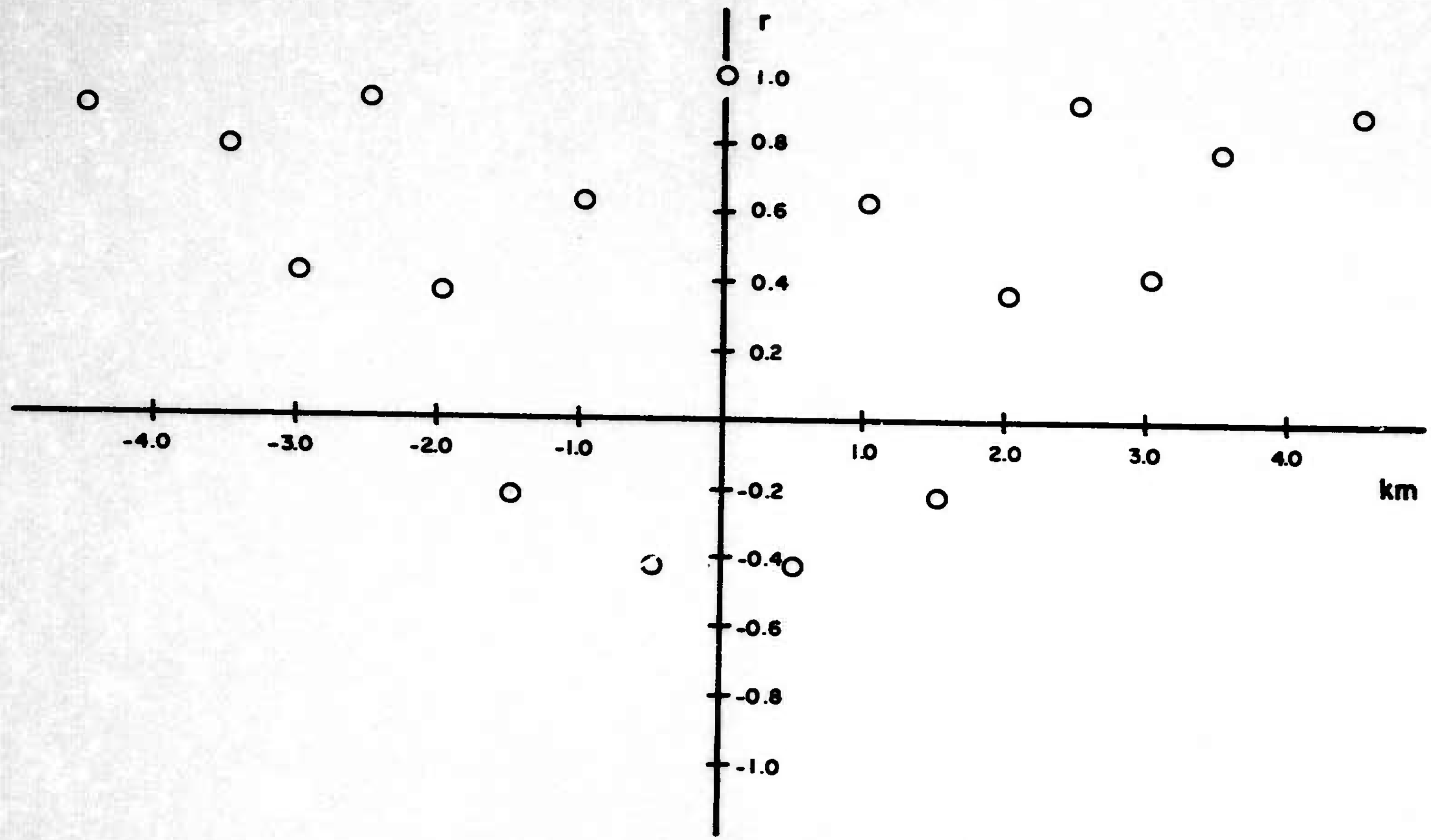

Figure 17. N. Colombia, 12 June 1966
Seismogram No. 7635, C4,
Leg 2

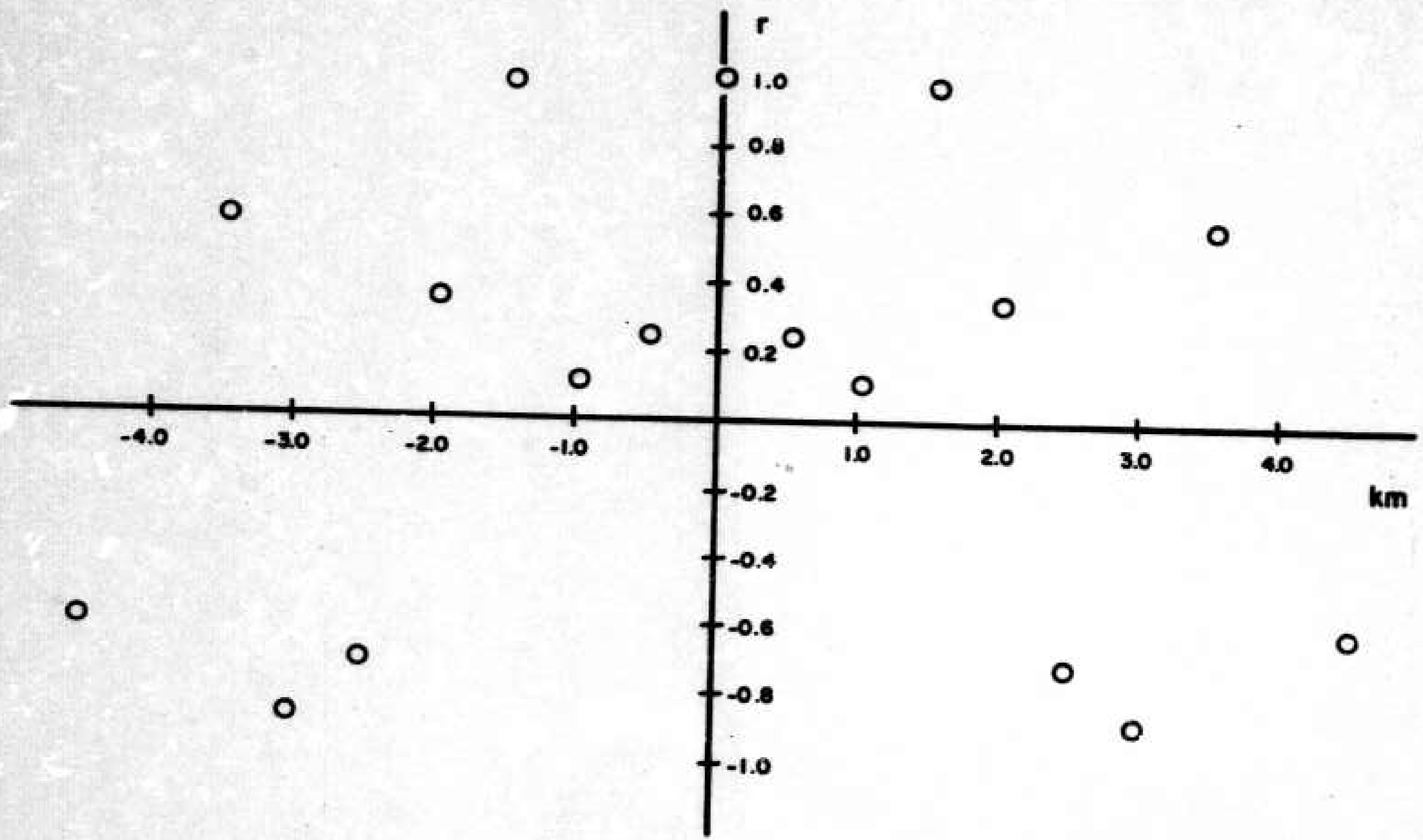

Figure 18. N. Colombia, 12 June 1966
Seismogram No. 7635, C4,
Leg 3

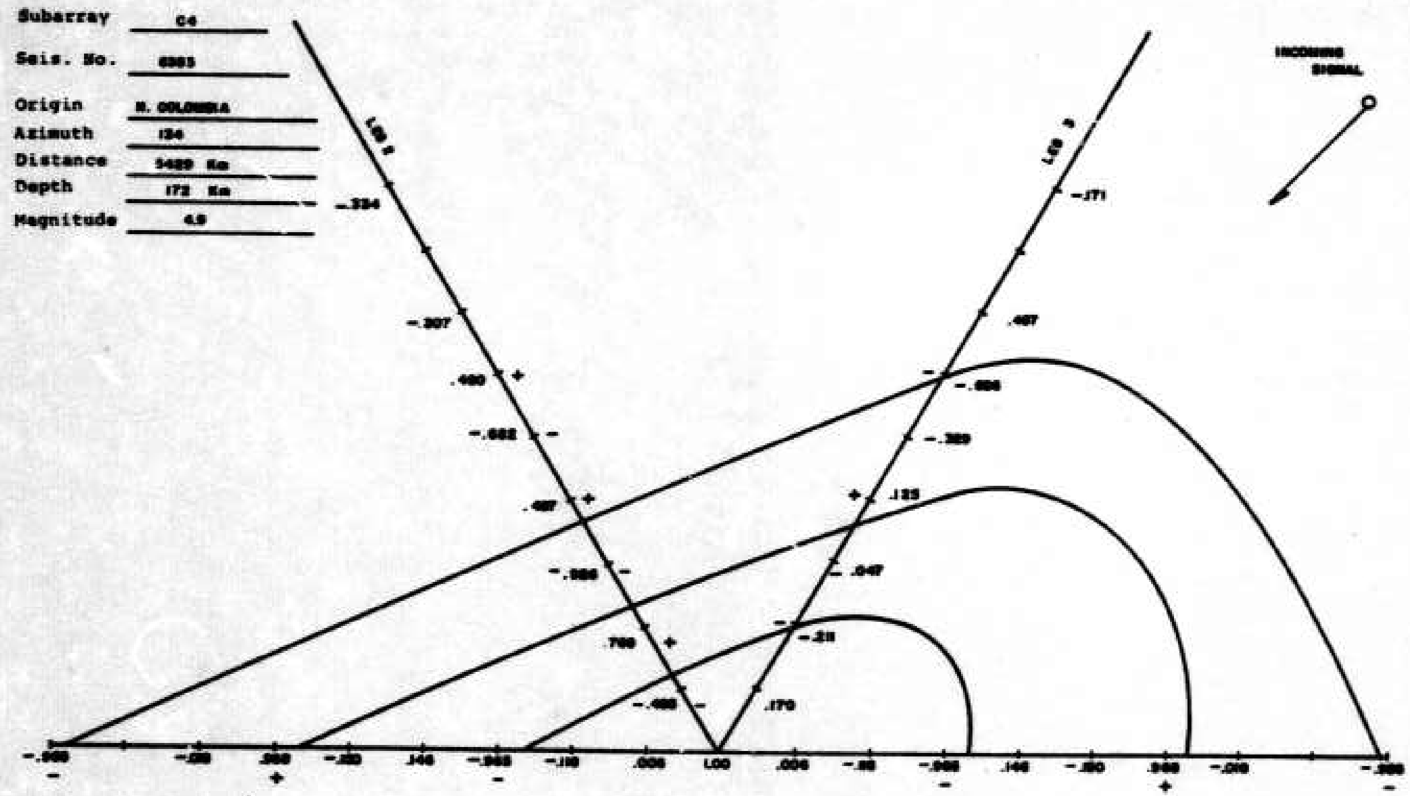
Subarray
C4
Seis. No.
Origin
Azimuth
Distance
Depth
172 Km
Magnitude
INCOMING SIGNAL

Figure 19

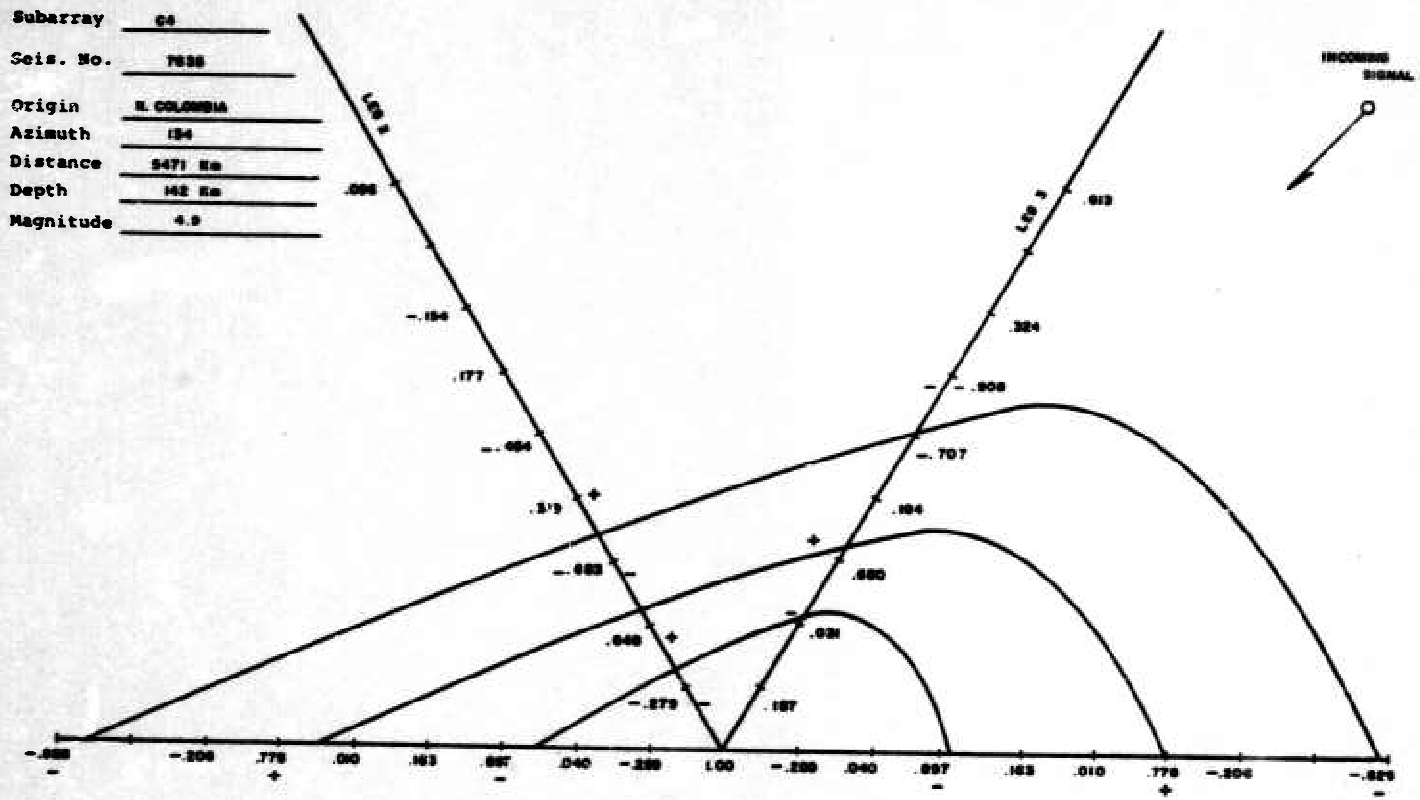
Subarray
Seis. No.
Origin
Azimuth
Distance
Depth
Magnitude
4.9
INCOMING SIGNAL
.324
-.707
.177
1.00

Figure 20

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13. ABSTRACT

Spatial correlations of amplitude anomalies have been conducted over LASA and LASA subarrays to test the hypothesis that these anomalies exhibit spatial stationarity. The evidence indicates that the anomaly process cannot be considered to be covariance stationary.

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	ROLE	WT	ROLE	WT	ROLE	WT
LASA P-Waves Amplitude Anomalies Correlation Techniques Seismometers						

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